

Stellar evolution on the Asymptotic Giant Branch

Albert A. Zijlstra

European Southern Observatory, Karl Schwarzschild Strasse 2,
D-85748 Garching bei München, Germany
email: azijlstr@eso.org

Review paper given at Edinburgh, August 1994, "Circumstellar Matter"

Abstract

Mass loss dominates the stellar evolution on the Asymptotic Giant Branch. The phase of highest mass-loss occurs during the last 1–10% of the AGB and includes the so-called Miras and OH/IR stars. In this review I will discuss the characteristics and evolution of especially Miras, and discuss how they are linked to the mass loss. There are indications that high mass-loss rates are only reached for relatively young stars with massive progenitors. The mass loss rates vary both on long and short time scales: the short-term variations are likely linked to luminosity variations associated with the thermal-pulse cycle. The influence of mass loss in the post-AGB phase is also discussed.

1 The Asymptotic Giant Branch

That Asymptotic Giant Branch (AGB) marks the end point of the evolution of stars with initial masses $\lesssim 8M_{\odot}$. Stars on the AGB are characterized by a degenerate C/O core, with nuclear burning taking place in a shell; the total AGB life time is of order 10^6 yr. A recommended review of AGB evolution can be found in Iben & Renzini (1984), although many of the numerical results have been updated since (e.g. Vassiliadis & Wood 1993).

During the first 90% of the total AGB life time the energy is provided by helium shell burning. This phase is called the early AGB, and is marked by a steady increase in luminosity. The early AGB ends when the helium, itself the remnant of earlier hydrogen burning, is finally exhausted and hydrogen is re-ignited in a thin shell. This starts the thermal-pulsing AGB: after sufficient helium has formed, the helium ignites with a flash (the thermal pulse; TP) followed by a new phase of helium burning. After the helium is again exhausted the cycle reruns. Typical time scales between thermal pulses are from 10^4 yr for the most massive stars to $> 10^5$ yr at low masses.

During the AGB the mass of the envelope surrounding the nuclear-burning shell is steadily reduced, by nuclear burning on the inside (increasing the mass of the C/O core) and mass loss through a stellar wind on the outside. When the remaining envelope mass has dropped below $0.05M_{\odot}$, the stellar temperature begins to increase and the so-called post-AGB phase starts. The temperature can reach values of 10^5 K (depending on mass) before nuclear burning ceases and the star enters the white-dwarf cooling track.

The best-known AGB stars are the Miras and OH/IR stars. Miras have typical luminosities slightly below $10^4 L_{\odot}$. They are large-amplitude pulsators with periods of 200–600 days. The periods are generally stable, but the amplitudes may vary in time. The observed luminosities of Miras, shown in Table I, indicate that they are located at the tip of the AGB. They are consistent with expected values for the TP-AGB even for the faint globular cluster Miras (Vassiliadis & Wood 1993, their table 2). The OH/IR stars are optically obscured stars, with very high mass-loss rates

Table 1: Mira bolometric magnitudes

population	M_{bol}	ref.
Galactic Centre	$-4.5 - -6$	Jones et al. 1994
Bulge	$-3.5 - -5$	Whitelock et al. 1991
Galactic Cap	$-3.5 - -5$	Whitelock et al. 1994
Metal-rich globular clusters	$-3 - -4.5$	Menzies & Whitelock 1985
LMC	≥ -7.2	Wood et al. 1992

and long periods of 1000–3500 days. It has been a long-standing problem whether they are more massive than the Miras or form a later evolutionary phase (e.g. Habing 1989).

In this review I will first discuss the luminosity variations on the AGB and the pulsations. The mass loss is discussed in Section 4, followed by some comments on the initial–final mass relation and the post-AGB evolution.

2 Luminosity variations

The luminosity during shell burning is in principle a monotonous function of core mass. Core mass–luminosity relations have been derived by many authors: a review which is still useful can be found in Boothroyd & Sackman (1988b). From this one derives the classical AGB limit of $M_{bol} = -7.2$ for the highest possible core mass of $1.4M_{\odot}$. This relation is calculated for quiescent hydrogen burning. Thus, it cannot be used for phases of helium burning, and during the first thermal pulses the quiescent luminosity is in fact not reached. The core mass here refers to both the C/O core and the helium shell.

Strong deviations from the M_cL relation occur at times. First, there is a strong effect on L during the TP, as shown in Figure 1. A substantial luminosity dip occurs during quiescent helium burning which lasts up to 30% of the cycle (Boothroyd & Sackmann 1988a, Vassiliadis & Wood 1993). For stars with low envelope mass (i.e. all low-mass stars) the TP causes a brief but large luminosity increase lasting $\lesssim 10^3$ yr. For stars with high envelope mass this increase is much less pronounced. Second, for massive stars with high-mass envelopes, the base of the convective envelope may penetrate the hydrogen-burning layer. This will temporarily increase the luminosity of the star (Blöcker & Schönberner 1991), although by how much is not clear (Vassiliadis and Wood 1993). When the envelope mass decreases, deep convection ceases and the star will appear to evolve *down* the AGB. Because of these deviations it is dangerous to derive a core mass from observed AGB luminosities for individual stars.

Wood et al. (1992) argue that there is no evidence for overluminous AGB stars in the LMC which might be expected from envelope burning. This is based on the lack of stars with $M_{bol} < -7.2$. However, AGB core masses possibly do not exceed $1.1M_{\odot}$, as indicated by initial–final mass relations (e.g. Weideman 1987). If this is the case, the limiting magnitude derived from the luminosity–core mass relation is closer to -6.9 and there would be some overluminous stars in the LMC.

3 Pulsations and the PL relation

Optical Miras show a strong period–luminosity relation, in the sense that higher luminosity coincide with longer periods. The relation is quite narrow in the K-band; it shows more scatter when the bolometric luminosity is used. The relation has been interpreted as an evolutionary sequence, but this is unlikely for several reasons: (1) Mira life times ($\sim 10^5$ yr) are too short to give an appreciable evolution in L . (2) Miras in individual globular clusters show a very small range in luminosity. (3) For Galactic Miras the velocity dispersion is a function of period (Table II, from Feast 1989)

Figure 1: (Taken from Vassiliadis & Wood 1993) Variations of stellar parameters during the thermal-pulse cycle. The period is calculated assuming fundamental mode; V_{exp} is derived from the period. \dot{M}_6 is the mass-loss rate in units of $10^{-6}M_{\odot}yr^{-1}$

Table 2: (From Feast 1989) Mira velocity dispersions

Period range (days)	asymmetric drift (km/s)	σ_T (km/s)	no. of stars
< 140	-33 ± 13	81	22
145–200	-111 ± 22	180	46
200–250	-61 ± 22	101	71
250–300	-33 ± 10	88	77
300–350	-32 ± 6	69	83
350–410	-23 ± 8	58	54
>410	-15 ± 8	50	35

Figure 2: (Taken from Feast 1989) The Miras and SR variables in globular clusters, together with the pre-Mira evolutionary track suggested by Whitelock (1986). The Mira period–luminosity relation (Feast et al. 1989) is shown for comparison.

indicating older progenitors for shorter-period Miras. (The shortest-period Miras ($P < 145$ days) have lower velocity dispersion than expected and may be a different group of objects, possibly higher-overtone pulsators.) Thus, it appears that the relation traces stars with different progenitor mass, with longer periods implying younger, more massive stars. Metallicity may also play a role.

Whitelock (1986) has shown that in globular clusters, semiregular variables and Miras define a sequence in the PL diagram which is much shallower than the Mira PL relation (Figure 2). The sequence has the same slope as found in recent theoretical calculations (Vassiliadis & Wood 1993, their figure 20) although it is shifted towards shorter periods. It seems likely that the Whitelock relation is the true evolutionary sequence and that the semi-regular variables form a pre-Mira phase.

During the thermal-pulse cycle, the changing characteristics of the star will affect the periods. This is shown in Figure 1: the star will move up and down (but not away from) the PL relation. This behaviour would of course not be observed if the Mira phase is confined to a single phase of the thermal-pulse cycle. A large shift up the PL could occur during the luminosity spike following a TP. Even though this spike is very brief, Mira pulsations could be triggered by a resonance because the nuclear time scale of the pulse is of the same order as the pulsation. In conclusion, although the PL relation does not appear to be an evolutionary sequence, movement up and down the relation

could still occur.

The PL relation holds for $P < 400$ days. For longer periods the scatter in P becomes very large and in fact it is not obvious whether any relation still exists (e.g. Wood et al. 1992, their figure 8). The relation could be broadened by envelope removal through mass loss which would increase the period; this could be especially important for more massive stars. A mode change to a lower pulsation mode would also have this effect. In contrast, contraction of the star, which occurs at the start of the post-AGB evolution will shorten its period.

Pulsation mode. Whether Miras pulsate in the fundamental mode or in an overtone has been a long-standing problem. The existence of a clear P-L relation implies that all Miras with $P < 400$ days have the same pulsation mode. (For the long-period OH/IR stars the absence of a clear relation does not allow one to extrapolate this conclusion.) In recent years the fundamental mode has generally been favoured: the evidence in favour is reviewed by Wood (1989) and is mainly based on observed shock velocities. However, the observed T_{eff} of the stars is lower than predicted from the fundamental mode. This was recently confirmed by angular diameter measurements of R Leo (Tuthill et al. 1994) which can exclude the fundamental mode for this Mira. There are also a few Miras known with multiple periods. In the case of IZ Peg, the periods are 488 and 345 days (Whitelock et al. 1994): if these are both modes of the star, the fundamental mode would have a period close to 1000 days. Finally, from a Fourier analyses of two Miras, Barthés & Tuchman (1994) favour first-overtone pulsations. Thus, although the situation is by no means clear, the balance is shifting to Miras being overtone pulsators.

Whitelock (1986) has suggested that metal-poor stars pulsate in the fundamental mode, while metal-rich stars pulsate in the first overtone. Since only metal-rich clusters contain Miras, this would imply that all Miras pulsate in the overtone.

4 Mass loss

Mass loss occurs along both the first giant branch (RGB) and the AGB, but only reaches catastrophic values at the tip of the AGB. Here values of $10^{-5} M_{\odot} yr^{-1}$ or higher are reached, which means that the envelope is removed much faster by mass loss than by nuclear burning. Thus, catastrophic mass loss will terminate the AGB, and the time at which it occurs determines the final core mass.

The IRAS colours of AGB and RGB stars show a gap between stars with essentially stellar colours at 12, 25 and $60\mu m$, and 'dusty' stars with significant excess (van der Veen & Habing 1988). Fitting the infrared spectra with a dust model, it appears that the gap coincides with mass-loss rates $\lesssim 10^{-7} M_{\odot} yr^{-1}$. In contrast, optical and UV observations show that essentially all red-giant stars show mass loss, often with mass-loss rates as low as $10^{-10} M_{\odot} yr^{-1}$ (e.g. Judge & Stencel 1991). These low mass-loss rates are not seen in the infrared and appear to be 'dustless'.

All Miras have 'dusty' IRAS colours and thus exhibit substantial mass-loss rates. Semi-regular variables, on the other hand, are found in both categories. If we identify these with pre-Mira stars, the conclusion is that 'dusty' mass loss begins during the semi-regular phase and that the mass-loss rate correlates with the amplitude of the pulsation. Very high mass-loss rates are only found for long-period Miras with $P > 400$ days, as shown by Jura (1986) for carbon stars and Whitelock et al. (1994) for oxygen stars. Combining this with the results from the previous section, this implies that high mass-loss rates are in general not reached for the lowest-mass stars; for instance, it is doubtful whether our Sun will ever become such a long-period Mira. However, low-mass stars could mimic this behaviour during the brief high-luminosity phase following a thermal pulse.

At present there is no theoretical model which can actually predict the mass loss. However, it is generally supposed that mass loss occurs in two stages. One mechanism such as pulsations or other long-term variability heats the atmosphere and causes it to extend to several stellar radii. At that distance dust forms and the radiation pressure on the dust will accelerate the shell and amplify the mass-loss rate. This model naturally leads to the expectation that there are two evolutionary phases: (1) At low mass-loss rates, the densities are so low that even if dust still forms, it will not be dynamically coupled to the gas. In this case mass loss is driven solely by the mechanism which

heats the envelope; (2) At higher mass-loss rates the gas couples to the gas and mass loss becomes more efficient and larger. The first phase would then be associated with the 'dustless' RGB and early AGB, the second phase is when the mass loss suddenly becomes catastrophic. Calculations on the dust-to-gas coupling have been done by MacGregor & Stencel (1992) and Netzer & Elitzur (1993). In either case, in principal the mass-loss rate would be determined by the fundamental stellar parameters, and could be quantified.

Such parametrizations are indeed available. The oldest is the well-known Reimers law (1975):

$$\dot{M} = -4 \times 10^{-13} \frac{LR}{M} M_{\odot} \text{yr}^{-1}$$

with L, M, R in solar units. This relation was derived from data on K stars and is known to predict too low rates from late AGB stars. Fitting model results from Bowen (1988), Blöcker (1993) has proposed a stronger dependence on L and M :

$$\dot{M} = -4.8 \times 10^{-9} \frac{L^{2.7}}{M^{2.1}} \frac{LR}{M} M_{\odot} \text{yr}^{-1}$$

This, however, predicts mass-loss rates close to $10^{-3} M_{\odot} \text{yr}^{-1}$ which are not observed. Although it is possible that the phase with such high mass-loss rates lasts too short to be observable, from stellar population studies in the LMC, Groenewegen and de Jong (1994b) and Groenewegen et al. (1994) conclude that this formula overestimates mass-loss rates by factors of 3–10.

The best observationally-established relation is given by Judge & Stencel (1991) for a sample of RGB and AGB stars. They find a good correlation between \dot{M} and $\log g$, which can be converted to a similar relation as above:

$$\dot{M} = (2.3 \pm 1.3) \times 10^{-14} \left(\frac{R^2}{M} \right)^{1.43 \pm 0.23} M_{\odot} \text{yr}^{-1}$$

This is close to Reimers' law with L replaced by R , a reasonable substitution since the two appear to be correlated during this phase of the evolution. Although the observational spread in the relation is significant, and especially the luminous carbon stars at the tip of the AGB fall above the relation, it is probably the best one to use in model calculations.

Vassiliadis & Wood (1993) have suggested that momentum in the wind should not exceed that in the radiation field, which for AGB stars implies $\dot{M} \lesssim 3 \times 10^{-5} M_{\odot} \text{yr}^{-1}$. They calculate mass-loss rates from a PL relation which is very steep, and Groenewegen & de Jong (1994b) find that their results do not fit the observed stellar population in the LMC. However, it is possible that the momentum limit should be included in the above relations.

Mass-loss variations. The above formulae predict that (1) \dot{M} increases with time on the AGB, (2) significant variations should occur following a thermal pulse due to the change in surface parameters. Thus, both long-term and short-term variations are expected. The short-term variations occur on time scales comparable to or shorter than the expansion of the nebula and should be observable.

The luminous OH/IR stars, which show very high mass-loss rates, often show very faint CO emission (Heske et al. 1990). Schutte & Tielens (1989) interpret this as evidence that the outer shell, where the CO emission originates, traces a lower mass-loss phase. The increase in \dot{M} would date back to $\sim 10^4$ yr ago. These time scales are consistent with those of the thermal pulse cycle, although it is not proven that the increase is related to this.

Figure 3 shows the IRAS colours for all M stars from the GCVS, using only data with good quality at all plotted bands ($q = 3$). The vertical lines connect points with the same mass-loss rates; horizontal lines connect points with the same outer radius, converted to a time using an expansion velocity of 10 km/s. There are at most very few sources for which the mass loss has started less than 10^3 yr ago. At $100\mu\text{m}$ almost all sources show a significant excess: this is either explained by a very shallow emissivity index (Rowan-Robinson et al. 1986) or an outer shell caused by earlier mass loss (e.g. van der Veen et al. 1994). Thus, mass loss generally continues for 10^3 yr or longer.

Interruptions of mass loss appear to be a common feature of optical carbon stars, which all show $60\mu\text{m}$ excess indicating a detached, cool shell. Willems & de Jong (1986) have proposed that this

Figure 3: IRAS colour-colour plots for M-stars taken from the GCVS. These will be mainly (but not exclusively) AGB and RGB stars. Model tracks at constant \dot{M} (vertical lines) and constant time scale (horizontal lines) are shown. (The absolute values for \dot{M} can change with assumed gas-to-dust ratio.)

occurs when due to a thermal pulse the C/O ratio becomes unity, with the resulting chemistry leading to a decrease in dust formation. This scenario predicts that the detached shells are oxygen rich. However, Bujarrabal & Cernicharo (1994) and Groenewegen & de Jong (1994a) find evidence that at least for some carbon stars the shells are carbon rich. Zijlstra et al. (1992) and Hashimoto (1994) show that some oxygen stars also show detached shells. This suggests that mass-loss interruptions may be a common phenomenon on the AGB and are not limited to carbon stars. It would seem logical to associate these interruptions with the phase of quiescent helium burning during the TP cycle, when the luminosity is lowest (e.g. Olofsson et al. 1990). Zijlstra et al. conclude that mass loss on the AGB contains a *periodic* component.

Implications In conclusion, high mass-loss rates coincide with high luminosity. This indicates that the primary factor determining the mass-loss rate is stellar mass, although low-mass stars could briefly obtain these luminosities during a thermal pulse. If mass loss varies through the TP cycle, as is likely, stars may pass through several mass-loss episodes, each lasting of order 10^4 yr. Because of the dust/gas decoupling, there may be a limit below which \dot{M} may drop by one or more orders of magnitude. This could amplify the effect of the TP-cycle.

5 Initial-final mass relation

The mass loss determines the mass of the core of the final white dwarf, and thus the initial-final mass relation. This relation is poorly constrained by observations: the only limits are given by a few white dwarfs in young clusters (Weideman 1987, Vassiliadis & Wood 1993). Applying the mass-loss relations above to theoretical models of AGB stars (Groenewegen & de Jong 1994b) leads to results consistent with these limits. Specifically, the relation is flat for $1-3M_{\odot}$ stars which all end up as white dwarfs with masses around $0.6M_{\odot}$. Higher-mass stars end up as heavier white dwarfs, but the Chandrasekhar limit is never reached: the most massive AGB stars leave $1-1.2M_{\odot}$ remnants. This has important consequences for the white-dwarf mass distribution. Han et al. (1994), following earlier suggestions, have shown that the observational constraints are well matched if one assumes that the envelope is lost shortly after the binding energy of the envelope becomes positive. Their relation could possibly be taken as a lower limit to the initial-final mass relation.

6 Post-AGB

The AGB ends when the stellar temperature begins to rise: the following phase is normally called the post-AGB. The mass loss continues into the early post-AGB phase as indicated by observational time scales: if the decrease in envelope mass (which determines how fast the stellar temperature increases) were only due to nuclear burning, it would take so long to reach the planetary-nebula phase that the nebula would long have disappeared. Schönberner (1983) has assumed that the high mass loss ends when the star first reaches $T_{eff} = 5500$ K. This is consistent with the fact that there are many optically visible post-AGB stars of type F and later, but almost none of K (Waters et al. 1989). However, van der Veen et al. (1994) present a few cases where a significant cooler star has a detached shell. The details of how the mass loss ends are still very unclear.

In a close binary system where one of the components passed through the AGB, it is possible that part of the shell may be retained in a circum-binary disk. This mechanism has been invoked to explain the extreme metal deficiency of some post-AGB stars (Van Winckel et al. 1992, Waters et al. 1992). It could also explain why highly obscured post-AGB stars invariably have bipolar shells: only objects where part of the shell remains close to the star will show high obscuration during the post-AGB phase (e.g. Siebenmorgen et al. 1994), and the binary nature of these objects could cause the non-sphericity of the shells.

Because the helium-burning phase in the TP cycle is relatively short, it is commonly assumed that almost all post-AGB stars have left the AGB as hydrogen burners. However, Vassiliadis (1993) argues that 25–50% of all post-AGB stars are helium burners, based on his evolutionary models. The reason is that for high-mass stars, the time the post-AGB star is visible is much longer for

helium burners than for hydrogen burners, thus biasing the statistics. In addition, for low-mass stars the mass loss may strongly peak immediately after a pulse thus increasing the likelihood the envelope will be lost at this time. Therefore, both the highest and lowest-mass stars may often be helium burners. The expected relative numbers of helium burners is strongly depended on poorly understood details of the mass-loss process.

For hydrogen-burning stars, there is a chance that a final thermal pulse will occur during the post-AGB evolution or even in the white-dwarf phase. It is thought that this may lead to a final phase of high mass loss, in which the entire remaining hydrogen layer is removed. The mass loss in this phase will be hydrogen-poor leading to strong infrared (dust) emission. Although a rare phenomenon, there are in fact stars which appear to have very recently entered this phase, in particular FG SGE (e.g. van Genderen 1994) and N66 in the LMC (Peña et al. 1994). Especially the latter is a good candidate for studying this final episode of mass loss.

7 References

- Barthès, D., Tuchman, Y., 1994, *A&A*, 289, 429
 Blöcker, T., Schönberner, D., 1991, *A&A*, 244, L43
 Blöcker, T., 1993, *Acta Astronomica*, 43, 305
 Boothroyd, A.I., Sackmann, I.-J., 1988a, *ApJ*, 328, 632
 Boothroyd, A.I., Sackmann, I.-J., 1988b, *ApJ*, 328, 641
 Bowen, G.H., 1988, *ApJ*, 329, 299
 Bujarrabal, V., Cernicharo, J., 1994, *A&A*, in press
 Feast, M.W., 1989, in: *The Use of Pulsating Stars in Fundamental Problems of Astronomy*, ed. E.G. Schmidt (Cambridge University Press), p.205
 Feast, M.W., Glass, I.S., Whitelock, P.A., Catchpole, R.M., 1989, *MNRAS*, 241, 375
 Groenewegen, M.A.T., de Jong, T., 1994a, *A&A*, 282, 115
 Groenewegen, M.A.T., de Jong, T., 1994b, *A&A*, 283, 463
 Groenewegen, M.A.T., van den Hoek, L.B., de Jong, T., 1994, *A&A*, in press
 Habing, H.J., 1989, in: *From Miras to Planetary Nebulae: which path for stellar evolution?* (Editions Frontières, Gif sur Yvette), p.16
 Han, Z., Podsiadlowski, Ph., Eggleton, P.P., 1994, *MNRAS*, 270, 121
 Hashimoto, O., 1994, *A&ASS*, in press
 Heske, A., Forveille, T., Omont, A., van der Veen, W.E.C.J., Habing, H.J., 1990, *A&A*, 239, 173
 Iben Jr., I., Renzini, A., 1983, *ARA&A*, 21, 271
 Jones, T.J., Gehrz, R.D., Lawrence, G.F., McGregor, P.J., 1994, University of Minnesota preprint
 Judge, P.G., Stencel, R.E., 1991, *ApJ*, 371, 357
 Jura, M., 1986, *ApJ*, 303, 327
 MacGregor, K.B., Stencel, R.E., 1992, *ApJ*, 397, 644
 Menzies, J.W., Whitelock, P.A., 1985, *MNRAS*, 212, 783
 Netzer, N., Elitzur, M., 1993, *ApJ*, 410, 701
 Olofsson, H., Carlström, U., Eriksson, K., Gustafsson, B., Willson, L.A., 1990, *A&A*, 230, L13
 Peña, M., Torres-Peimbert, S., Peimbert, M., 1994, *ApJ*, 428, L9
 Reimers, D., 1975, in: *Problems in Stellar Atmospheres and Envelopes*, Bascheck et al., eds. (Springer, Berlin) p.229
 Rowan-Robinson, M., Lock, T.D., Walker, D.W., Harris, S., 1986, *MNRAS*, 222, 273
 Schönberner, D., 1983, *ApJ*, 272, 708
 Schutte, W.A., Tielens, A.G.G.M., 1989, *ApJ*, 343, 369
 Siebenmorgen, R., Zijlstra, A.A., Krügel, E., 1994, *MNRAS*, in press
 Tuthill, P.G., Haniff, C.A., Baldwin, J.E., Feast, M.W., 1994, *MNRAS*, 266, 745
 van der Veen, W.E.C.J., Habing, H.J., 1988, *A&A*, 194, 125
 van der Veen, W.E.C.J., Waters, L.B.F.M., Trams, N.R., Matthews, H.E., 1994, *A&A*, 285, 551
 van Genderen, A.M., *A&A*, 284, 465
 Van Winckel, H., Mathis, J.S., Waelkens, C., 1992, *Nature*, 356, 500

- Vassiliadis, E., 1993, *Acta Astronomica*, 43, 315
- Vassiliadis, E., Wood, P.R., 1993, *ApJ*, 413, 641
- Weidemann, V., 1987, *A&A*, 188, 74
- Whitelock, P.A., 1986, *MNRAS*, 219, 525
- Whitelock, P.A., Feast, M.W., Catchpole, R.M., 1991, *MNRAS*, 248, 276
- Whitelock, P.A. et al. 1994, *MNRAS*, 267, 711
- Waters, L.B.F.M., Waelkens, C., Trams, N.R., 1989, in: *From Miras to Planetary Nebulae: which path for stellar evolution?* (Editions Frontières, Gif sur Yvette), p.449
- Waters, L.B.F.M., Trams, N.R., Waelkens, C., 1992, *A&A*, 262, L37
- Willems, F.J., de Jong, T., 1986, *ApJ*, 303, L39
- Wood, P.R., 1989, in: *From Miras to Planetary Nebulae: which path for stellar evolution?* (Editions Frontières, Gif sur Yvette), p. 67
- Wood, P.R., Whiteoak, J.B., Hughes, S.M.G., Bessell, M.S., Gardner, F.F., Hyland, A.R., 1992, *ApJ*, 397, 552
- Zijlstra, A.A., Loup, C., Waters, L.B.F.M., de Jong, T., 1992, *A&A*, 265, L5